Environmental assessment of Braskem's biobased PE resin

Summary of the life cycle assessment, land-use change and water footprint reports

November 2013

This is a summary of a report prepared by E4tech and LCAworks in collaboration with two expert reviewers, Professor Isaias Macedo and Professor Joaquim Seabra.

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Introduction

In order to better understand the environmental profile of its polyethylene resins derived from biobased feedstock (sugarcane ethanol), Braskem commissioned three separate, but related studies:

1. A complete life cycle assessment in line with ISO 14040/44
2. A location-specific land use change assessment in line with the EU Renewable Energy Directive
3. A location-specific water footprint based on the Water Footprint Network methodology

Practitioners

The studies were developed by E4tech, a technically informed strategic consultancy in sustainable energy and materials based in the UK and Switzerland, and LCAworks, an environmental consultancy based in the UK. They relied on data collected from a selection of Braskem's ethanol suppliers and on Braskem data for the polyethylene resins production processes, and benefited from close collaboration between the two firms and two independent Brazilian experts. The three studies investigate different aspects of the cradle-to-(factory) gate life cycle impacts of the production of Braskem's biobased high-density polyethylene (HDPE) and linear-low density polyethylene (LLDPE) resins.

Objectives

The main aims of the three studies were to:

- gain insight into the key impacts of biobased polyethylene resins production across a range of environmental impact categories
- consider the environmental profiles of novel biobased PEs, and in the case of the LCA compared with the environmental profiles of conventional petrochemical-based PEs (based on petrochemical PEs by Braskem from their production site at Triunfo, Rio Grande do Sul, Brazil).
- understand some of the wider environmental issues linked to the introduction of biobased PE manufacture
- evaluate opportunities to improve the environmental profile in the future.

Life cycle assessment - LCA

The LCA study was undertaken in accordance with ISO 14040/44, complemented by additional relevant parts of BS EN 16214 (Draft), BS EN 15804 (2012), PAS 2050 (2011), the Greenhouse Gas Protocol and the International Reference Life Cycle Data System (ILCD).

An ISO 14044 critical review process for this LCA study was carried out in 3 stages, with the Goal & Scope report issued to the Critical Review Panel (CRP) in January 2012, the review of the LCI raw data report completed in May 2013, and the final LCA report review and CRP statement in November 2013.

The CRP includes the following individuals:

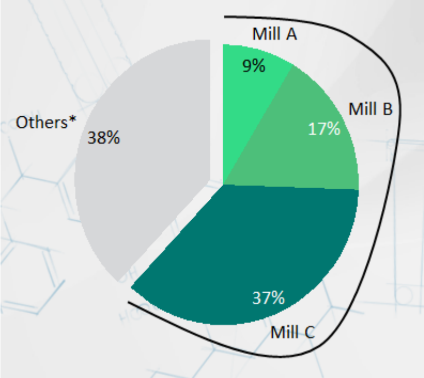
- Andreas Detzel, IFEU, Germany
- Prof Ramani Narayan, Michigan State University, USA
- Martina Krueger, IFEU, Germany (substituting Prof Masahiko Hirao, University of Tokyo, Japan, from October 2013)

Functional unit, data and methodological choices

The functional unit for the study is 1 kilogram of Braskem biobased PE resin, commercially known as *"I'm green^{TM} Polyethylene"*.

Primarily, the study focusses on the potential emissions and removals[1] related to the production of biobased PE products. It aims to understand the wider implications of the new biobased PE system, rather than only attributional aspects of the environmental profile for what could be regulatory compliance (e.g. similar to the EC Renewable Energy Directive for biofuels regulation). Thus, the LCA here considers aspects linked to the introduction of biobased PE that may affect removals and emissions more widely than just within the product system itself. Particular attention was paid to the potential implications of co-products, carbon removals into the PE products and effects of direct and indirect Land Use Change (direct LUC and indirect LUC). The principle approach used for presentation of the LCA results for the biobased PE is a *substitution credit approach* for electricity co-produced with ethanol and supplied to the Brazil national grid.

The LCA, land-use change and water footprint results are based on data from three individual mills that supply more than 60% of the ethanol purchased by Braskem. Their data is representative of the 2011/12 harvest year, and has been averaged over a full 6-year sugarcane crop cycle. Making up the remaining ethanol is a "Centre-South Brazil" dataset, representing the average ethanol supply from this region (which produces >80% of Brazilian sugarcane ethanol). This gives the "Braskem weighted average ethanol" supply based on the volumes of ethanol supplied by these different sugarcane mills.



Data for Braskem's manufacturing of biobased PE refers to the 2012 production year, representing stable manufacture processes. This is considered to be a reasonable reflection of production expected over the time period 2011-2015. Since the biobased ethylene plant start-up commenced in 2011, 2012 production still included periods of improvement and process refinement.

The assessment includes biobased HDPE produced by either the slurry process (Hostalen) or HDPE or LLDPE produced by the gas-phase process (Spherilene) up to the Braskem factory gate in a form ready for compounding and packaging for distribution to users. The analysis revealed only small differences between the slurry and gas phase results for the manufacture of biobased PE in any impact categories with other factors constant. This is the reason why the gas-phase data is not presented in this summary report.

Conventional HDPE and LLDPE resins produced by Braskem from Naphtha are also assessed in the report as comparative benchmarks and these are referred to as petrochemical HDPE and petrochemical LLDPE respectively. Again, this summary report only presents the HDPE, as differences between the petrochemical PEs are relatively small.

Several sensitivity analyses were carried out to ensure the quality of the results and guarantee a transparent and robust study that best represent the Brazilian conditions and Braskem's reality.

This executive summary presents detailed results generated for the "Base case" as defined below:

1 kg of Green HDPE (slurry process, "Braskem weighted average" ethanol supply) when a substitution credits methodology (consequential LCA approach) is applied to the surplus

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[1] The term "removals" is here used to express what is often referred to as "sequestration". Since this study is cradle to gate, the term "sequestration" is avoided in order not to imply a false sense of "permanent" storage of CO_2 from the atmosphere, when, in fact, this CO_2 could be released again depending on the fate of the PE product in the end of life phase of a full life cycle.

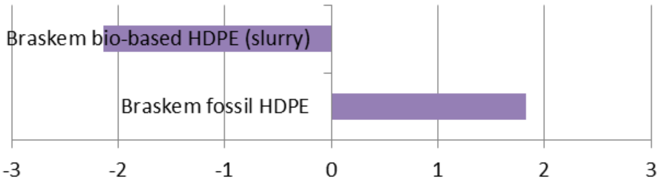
electricity co-product and when CO_2eq credits for direct LUC carbon storage on land and CO_2 removal into the polymer resin are accounted for in the model

Results

The graphs below present the comparison of the Braskem "Base Case" biobased PE produced via the slurry process and Braskem's petrochemical PE (a single site, like-for-like comparison). The results are expressed as LCIA results, primarily via midpoint assessment methods.

Note that these impact categories present "potential" impacts, and not impacts that have been directly measured in the environment. It is also not possible to simply derive the sustainability of these processes in the relevant locations from these results. This would require further detailed location-specific research.

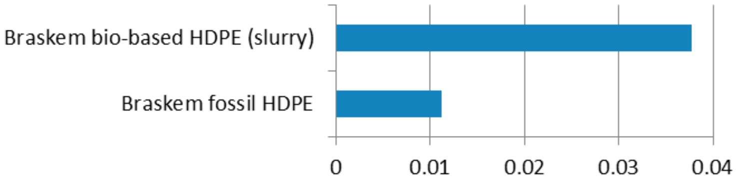
Global Warming Potential (kg CO_2eq/kg PE)



Calculation methodology: IPCC 2007

This presents the GHG emissions of the two PE products.
For the biobased PE, this figure is negative. The main reasons for this are carbon "removal" from the atmosphere and its incorporation as carbon atoms in the polymer (as "sequestered" CO2), but also a "substitution credit" for co-produced electricity at the sugarcane mills and for direct land-use change.

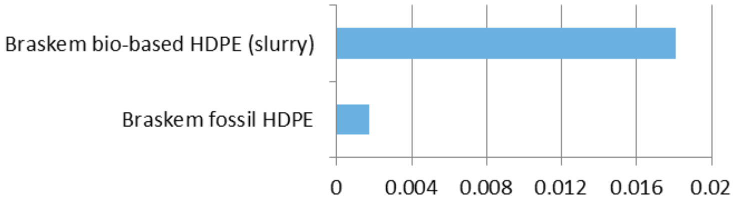
Acidification Potential (kg SO_2eq/kg PE)



Calculation methodology: CML 2001

This describes any potential chemical alteration of the environment (mainly rivers and lakes) resulting in hydrogen ions being produced more rapidly than they are dispersed or neutralised.
The main contributors to this impact category are SOx and NOx emissions. For biobased PE they result from bagasse combustion, fossil fuel combustion by agricultural machinery and in- field trash burning.

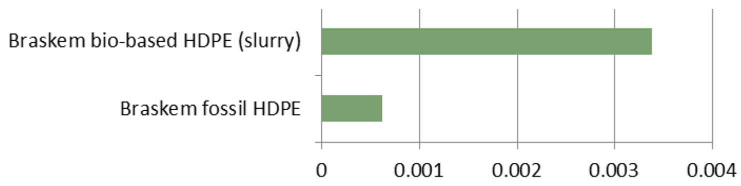
Eutrophication Potential (kg PO_4eq/kg PE)



Calculation methodology: CML 2001

This informs on the potential enrichment of land and water bodies by nitrogen and phosphorous compounds from emissions to air or surface run-off. Enrichment increases the growth of aquatic plants and can produce algal blooms that deoxygenate water and smother other aquatic life.
The emissions that drive the eutrophication category of the biobased PE are primarily from sugarcane cultivation and mainly phosphate and phosphorus emissions.

Photochemical Ozone Creation Potential (kg C_2H_4eq/kg PE)

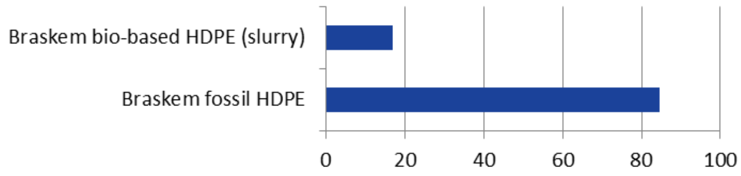


Calculation methodology: CML 2001

Photochemical ozone formation is caused by degradation of organic compounds (VOCs) in the presence of light and nitrogen oxide (NOx), causing "summer smog" as a local impact and "tropospheric ozone" as a regional impact.

The main contributors to this impact category for biobased PE are the sugarcane cultivation, and green ethanol production, with sugarcane production the most significant driver due to the carbon monoxide from in-field trash burning.

Fossil Energy Demand (MJ/kg PE)



Fossil energy demand represents a depletion of these finite reserves. Petrochemical PE's fossil energy demand includes fossil feedstock that is converted into the PE polymer itself as well as fossil process energy usage for this conversion. Biobased PE's fossil energy demand is incurred in sugarcane cultivation, ethanol transport and green ethylene production and polymerisation into biobased PE. However, its feedstock is renewable (sugarcane ethanol) as is over 80% of the energy for its processing (sugarcane bagasse). Both types of PE share the same polymerisation process, i.e. they have the same fossil energy demand for that particular phase of production.

Exploration of scenarios

By working through different scenarios, insights can be gained on specific matters of interest, for example related to the possible improvements that can be achieved, or if impacts can be expected to change in the future.

An ***improvement analysis*** on the base case revealed that a series of near-term measures in sugar cane cultivation and cane mill operations, as well as in the green ethylene conversion process would yield a 10-20% improvement across all assessed impact categories.

Equally, an analysis of the longer-term ***future perspective 2020*** revealed that strong indications that substantial opportunity exists to continue improving the environmental performance for biobased PE over that timeframe and beyond.

Main conclusions

The main conclusions from this cradle-to-factory gate LCA study are:

Global Warming Potential (GWP_{100}) impacts

- The two types of Braskem's biobased PEs, for the "Base Case" modelled using the substitution credit approach and the Braskem average ethanol supply chain lead to a negative GWP_{100}

indicator. The biobased PE polymer resin leads to a net removal of CO_2 from the atmosphere, averaging -2.15 kg CO_2e/kg biobased HDPE (slurry). The emissions from biobased PE production (sugarcane production, ethanol production, Green Ethylene production and biobased PE production) are more than outweighed by the CO_2 removed from the atmosphere and embodied into the biobased PE resin.

- Under the substitution credit methodological approach, a credit is awarded to sugarcane ethanol for the emissions avoided from power generation in natural gas power plants due to the green electricity co-produced with sugarcane ethanol. This benefit is equivalent to offsetting approx. 25% of the GWP_{100} production emissions for biobased HDPE (slurry) for Braskem's average ethanol supply.
- Direct LUC for sugarcane cultivation, as calculated by the separate LUC study (see below for more information), also contributes beneficially to the overall GWP_{100} balance for biobased HDPE (slurry) by offsetting the equivalent of 40% of the GWP_{100} production emissions for biobased HDPE (slurry) for Braskem's average ethanol supply.
- When compared with Braskem's petrochemical PE comparator in this study, which has a GWP_{100} impact of +1.83 kg CO_2e/kg PE, the net GWP_{100} benefits of the base case Braskem average biobased HDPE (slurry) is -3.98 kg CO_{2e}/kg biobased PE.
- Care must be taken when quoting the GWP_{100} balance results, to be clear that they refer to the co-product substitution credit methodology applied and that this is a cradle-to-gate assessment. A significant fraction of the negative GWP_{100} emissions associated with Braskem biobased PE is due to the carbon bound in the biobased PE, and the LCA does not account for the ultimate release into the atmosphere of any of this bound carbon, which could potentially occur as part of the ultimate fate of a biobased PE product. Of course, the same will also apply to the end of life of a petrochemical PE product.

All categories

The performance of biobased PE compared with the petrochemical comparator is mixed across the other environmental impact categories. Biobased PE shows benefit for Global Warming Potential (GWP) and Abiotic Depletion, but the petrochemical comparator performs better or equally across the other impact categories.

Although GHG/GWP and Abiotic Depletion issues are the most important drivers of green materials uptake, it is important to maintain a balanced perspective across a range of important environmental impacts. The relative weighting of different environmental indicators has been a topic of academic debate for several years, and attempts have been made to create integrated assessments based on different weighting approaches. In practice, the relative importance of each impact category varies according to the specific local conditions and needs to be interpreted and weighted very carefully in that context. Also, the significance of the absolute impacts needs to be understood, though the lower the impact the better.

Sensitivity Analysis

The sensitivity analysis carried out gives significant comfort that the results are not critically altered around a small number of (possibly uncertain) assumptions or input data. Overall, the broad conclusions from the results are relatively insensitive to most critical data, boundary and assumptions.

Impacts of transport

A question is often asked in relation to the impacts of transport. The relative contributions of transport to the six main environmental impact categories for Braskem's biobased HDPE (slurry) are dominated by the transport of the ethanol by rail in Brazil, owing to the large distances involved compared with road transportation, and higher per unit distance impacts than for transport by sea. The international shipping of biobased HDPE from the factory in Brazil to representative international destination ports adds only 2-4% extra to the GWP_{100} emissions profile.

"Hotspots"

In an approximate order of importance in relation to impacts:

HOTSPOTS	Impact Categories
Trash and bagasse burning	GWP, Acidification Potential, Eutrophication Potential, Photochemical Ozone Creation Potential
Fertilizer and pesticide use and soil/field emissions	Eutrophication Potential
Diesel consumption	GWP, Abiotic Depletion Potential
Natural gas usage	GWP, Abiotic Depletion
Transportation	GWP, Abiotic Depletion Potential, Acidification Potential, Eutrophication Potential
Grid electricity use	GWP, Abiotic Depletion, Acidification Potential, Eutrophication potential

Main limitations of this study

A thorough and detailed LCA study underlies this summary. However, in common with most LCA studies, some important limitations are associated with methodology and data choices, data quality aspects and interpretations made.

- There are uncertainties (explored in the sensitivity analyses) associated with input data for some key substances and processes (e.g. phosphate leaching from fertilizer use, emissions to air from in-field, pre-harvest burning of sugarcane (being phased out) and from bagasse combustion). Further research would lead to more reliable values, and in several cases would require new measurements to be carried out. Sensitivity analysis showed that while the overall balance of results of the LCIA was relatively stable to a range of these values, some appreciable effects are observed for one or two individual impact categories. Overall these do not in themselves invert the trend in the findings.
- The methodologies used to analyse the inventory and to develop characterised results and their interpretation is still undergoing active development in the LCA community. At present, there is no universally agreed single 'consensus' approach. The LCA aimed to select impact categories and methodological approaches that are consistent with established European and International standards and guidance. The methodological choices used for this study are described explicitly in the full LCA report and a number of 'extra' impact categories beyond the six core ones were also explored in the work (e.g. terrestrial ecotoxicity). Sensitivity analysis using an alternative LCIA method (ReCiPE) was also undertaken and this supported the general direction of the results obtained.
- The choice of approach in relation to co-products, especially green electricity exported to the Brazilian national grid (co-product of sugarcane ethanol), is an important methodological aspect that affects the results. The study applies the substitution credit approach for co-product electricity, considering that it is a significant element in the Brazilian grid electricity supply and has been recognized and applied in similar studies both in Brazil and internationally. However, in order to ensure transparency and as a sensitivity analysis, results are also presented and discussed via the allocation approach in the full LCA report.

- The results and conclusions drawn from this study reflect the system and methodological choices made. Alternative methodological approaches, system boundaries and/or impact categories will lead to differences in the results.
- The cradle-to-gate perspective of this life cycle study properly reflects those phases of a product life cycle that are under Braskem's direct influence as manufacturer and supplier of biobased and petrochemical polyethylenes. As a cradle-to-gate study no account is taken of impacts associated with the use and end-of-life phases of a full product life cycle.

Land-use change assessment

Method

A separate, location-specific study on the land use change impacts of Braskem’s demand for sugarcane ethanol for the production of biobased PE has been conducted. This study estimates the changes in soil organic carbon and carbon stocks of land directly and indirectly affected by Braskem’s activities. An important objective of the study was not only to help Braskem better understand the land requirement fo biobased PE and the resulting impacts on the existing Brazilian agricultural system, but also to identify actions to mitigate land pressure and carbon emissions from such land use change.

Approach

The study is limited to changes in soil organic carbon and above and below ground carbon stocks, and quantifies the direct carbon emissions from conversion of land directly to sugarcane cultivation (direct LUC), as well as the indirect “knock-on” effects of displaced pasture and cropland to other regions in Brazil (indirect LUC). To understand impacts of future changes in sugarcane harvesting practices and intensification of the agricultural system, both a current case (2008 – 2011/12 harvest year) and a future case (2008 – 2020) were calculated and used in the appropriate scenarios in the LCA study. The direct LUC and indirect LUC impacts are calculated per kg biobased PE.

The direct LUC calculations follow the “European Commission Decision of 10 June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC”. The calculations include changes in soil organic carbon, above/below ground carbon stocks and the effects of the burning of cane and trash on carbon stocks. It was taken into account that soil organic carbon stocks only reach their equilibrium after approximately 20 years of consistent land cover or land use.

It is important to note that disagreement over the modelling of indirect LUC exists among practitioners and policy makers. For the indirect LUC modelling in this study, E4tech’s causal-descriptive modelling approach was used (E4tech, 2010[2]). This approach transparently models the local land use situation at the sugarcane plantations, and the knock-on impact of land required elsewhere. All assumptions were reviewed by local experts. However, the controversy and lack of consensus on indirect LUC representation means that, in common with many LCA studies it has not been implemented in the base-case. The potential effects of incorporating indirect LUC were examined in a specific scenario in the full LCA report.

Data – direct LUC

Analogous to the LCA study, the same three mills provided us with data regarding soil conditions and the mix of land types that were converted during expansion in 2010/11 and 2011/12 (for the “current” case), and which mix of land types they expect to continue to be converted in the future (2012-2020, “future” case), as well as the share of burned and unburned cane for both periods. A “São Paulo/Centre-South” data set was constructed based on literature data and local expert advice to determine LUC impacts of ethanol supply other than from the three mills. This was complemented with additional literature data in order to characterise soil organic carbon and above and below ground carbon stocks before conversion to sugarcane and after conversion.

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[2] E4tech (2010) “A Causal Descriptive Approach to Modelling the GHG Emissions Associated with the Indirect Land Use Impacts of Biofuels” Authors: Bauen, A., Chudziak, C., Vad, K., and Watson, P., Final Report, A study for the UK Department for Transport, Available at: http://www.apere.org/doc/1010_e4tech.pdf

The mills also provided us with the figures of their supply (or supply projections in the "future case") of ethanol to Braskem in the time periods considered. These figures were used to calculate the weighted average LUC of Braskem's ethanol consumption.

Data – indirect LUC

Since it is not possible to know exactly where the indirect LUC takes place and which land uses or land covers are displaced, for the indirect LUC modelling a regional dataset published by Winrock International (2011)[3] with estimates of historic proportions of different land cover changes and associated carbon stocks was used.

Results – direct LUC ("current case")

As presented in Figure 1, the weighted average across Braskem's current Green PE production equates to direct LUC emissions of -1.1 kgCO2e/kg PE, with a range of +0.7 to -2.4 kgCO2e/kg PE.

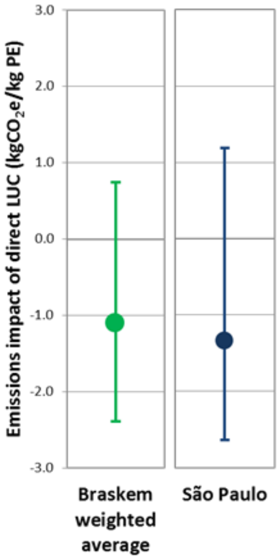

Figure 1: direct LUC results

We note that these "average" net CO_2 emissions for direct LUC are negative, i.e. the change to sugarcane has increased the carbon stocks in the soil and/or above and below-ground vegetation. The error bars in Figure 1 indicate uncertainty ranges that result from data sets with actual measurements lacking in many cases and the use of proxy data from literature. The error bars extend in the positive direction, i.e. it is not certain that Braskem's current Green PE production is leading to net CO_2 negative direct LUC.

Results – indirect LUC ("current case")

Given the methodological uncertainties, indirect LUC was not included in the "Base Case" scenario of the LCA study. Indirect LUC is found to result in +1.3 $kgCO_2e$/kg PE, but was not further used in LCA scenarios.

Results – "future case"

Both the direct and indirect LUC emissions show slight improvements in the future case. This is mainly due to the phase-out of the practice of burning of sugarcane during manual harvesting in the case of direct LUC, and due to further intensification and yield improvements in the case of indirect LUC.

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[3] Winrock International (2011) "Land Use Change GHG Emissions Factors", pdf and excel available at: http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2011-0542-0105

Conclusions and limitations of the study

Sufficient land is available to meet Braskem's demands. There are currently 9.75 million ha of sugarcane in Brazil. Brazil's Agro-Ecological Zoning policy identifies very large areas of land within Brazil that are suitable for the expansion of sugarcane production without environmental restrictions. Around 5-6 million ha of additional land is expected to be needed by 2020 for the sugarcane industry as a whole, based on current projected demands by Embrapa. The area modelled for Braskem's hypothetical 2020 production is only a very small fraction of this area.

The uncertainty of the data has to be taken into account whenever drawing inferences from the results of both the direct and indirect LUC impacts. More extensive and detailed data would reduce uncertainties, and improved data gathering at the sugarcane plantations would enable Braskem to model the impacts of LUC with greater precision in the future.

The key message from the available direct LUC data is to ensure that the soil types expanded onto are those that are likely to give the greatest gain in SOC, and that minimal above-ground vegetation is present. As the land types onto which a high proportion of sugarcane expansion is expected to occur are typically degraded pasture land, the resulting indirect LUC will also be relatively small.

Importantly, although the direct LUC results gave a spread of negative values (with uncertainties stretching into the positive), it is expected that the indirect LUC results will generally always be positive (due to conversion of higher carbon stock native vegetation), despite the large data uncertainties

Water footprint

A separate study on the water impacts of Braskem's demand for sugarcane ethanol for the production of biobased PE has been conducted, making use of data gathered for the LCA study and assuming the same system boundaries and temporal coverage.

Methodology

The assessment follows the methodology of the Water Footprint Network, thus calculating the direct and indirect water consumption of Braskem's biobased PE (for both the water consumed by sugarcane itself, the "green water footprint", and readily accessible water taken from aquifers and streams for process use the "blue water footprint"[4]) and an estimation of the water that would be needed to dilute any pollutants to legally acceptable levels (the "grey water footprint").

Figure 2 illustrates the calculation of the water footprint (WFP) for each of the production stages of biobased PE. The words "direct" and "indirect" highlighted in white indicate in which production stage either a direct or indirect green, blue, or grey WFP occurs. For example, only the plantation & mill (i.e. the ethanol production) stage has a direct green WFP generated by the uptake of rainwater by the sugarcane, while the indirect green WFP that occurs in the plantation & mill as well as in the transport stage comes from a very small amount of biodiesel used for machinery and trucks. Added up together, these components make up the total green WFP of Braskem's biobased PE. The figure also shows allocation to different co-products, which is done on an economic basis.

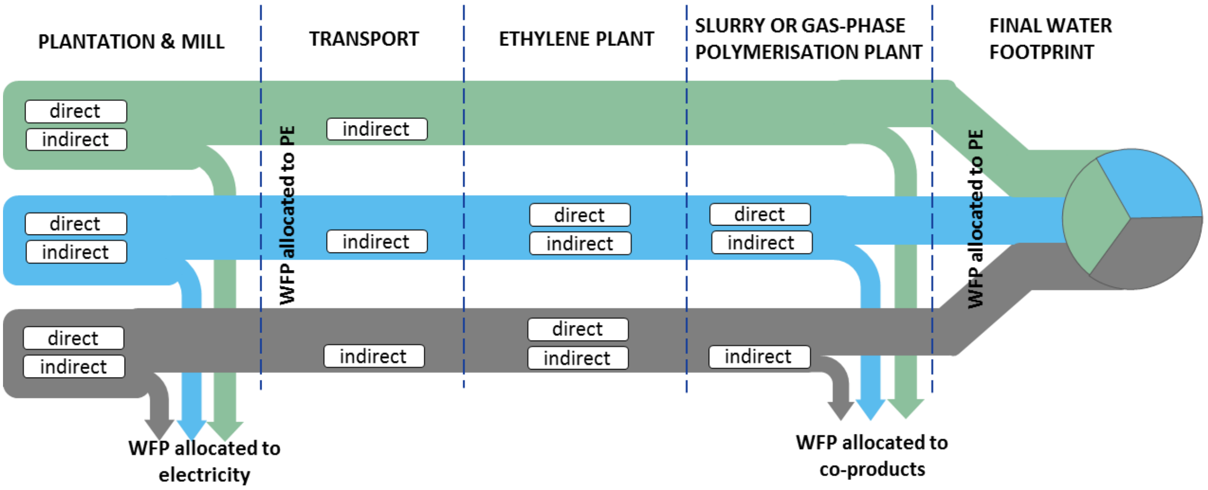

Figure 2: Illustration of the calculation of the overall WFP

The final results are then split up between the Parana River Basin, where all the sugarcane plantations and the ethanol mills are located, and the South Atlantic Basin, the location of Braskem's ethylene and polyethylene facilities.

In addition to this quantitative assessment, the study also gathers evidence of the underlying situation of these river basins: data is assembled about the availability of water as well as its quality using data published by governmental and international bodies. Based on these insights, we come to an initial understanding of the sustainability of the water impacts of Braskem's demand for sugarcane ethanol.

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[4] It is important to note that the "blue" water footprint is defined as the "removal" (either through incorporation into a product and its transport or evaporation) from the river basin in which a particular process step takes place.

Results

Figure 3 shows the water footprint (split into the green, blue and grey components) of Braskem's biobased PE production for the river basins in which the activities are located.

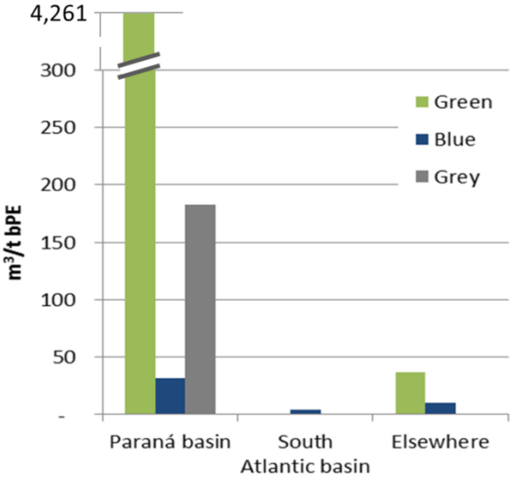

Figure 3: Water footprint of Braskem's biobased PE production in river basins where production is located

It is immediately evident that the green water footprint dwarfs both the blue and the grey water footprints. This result is the norm for products derived from plants, as they take up water through evapotranspiration during growth. There are no green and grey components in the South Atlantic Basin, as processing in this river basin does not involve the growing of sugarcane, and as Braskem's chemical plants only discharge treated liquid effluents.

The results have been compared to other water footprint studies of sugarcane and sugarcane ethanol, and were found to be slightly lower, with some sensitivity of the green water footprint to the underlying data for evapotranspiration.

For the sustainability assessment, both the availability and quality of water in both river basins was assessed:

According to data available for the Parana River Basin, even during the dry months water scarcity is considered to be low, and water supply sustainable throughout the year. In addition to this, sugarcane with its characteristically high green water footprint grows during the wet season, and is not irrigated in this area, making a negative impact on water availability unlikely.

Equally, water quality measurements attest an overall healthy situation. Overall in the Parana River Basin there is no immediate concern regarding water sustainability at this time, however, it is important to monitor the impact of the agricultural activities and their impact continuously.

In the South Atlantic Basin, data shows that the area is considered a hot spot both in terms of water availability and quality. From the data gathered for this study it is clear that Braskem's processes are water efficient, but it is vital that processes are reviewed and improved regularly, and that staff awareness around the issues of water is built and maintained.

Conclusions and limitations of the study

1. **Green water footprint** – determining the correct value of evapotranspiration is difficult as this parameter depends on rainfall, insolation and other general characteristics of the location of the field. Measurements of the same field in different years can also yield different values for

evapotranspiration. In addition, comparative green WFPs are needed in order to be able to assess the "net green WFP" when converting land from previous land uses to sugar cane plantations.

2. **Grey water footprint** – in the absence of a clearly agreed method for quantifying the dilution volumes for assimilation of pollutants, the estimation of the grey WFP is subjective. The authors suggest that issues such as eutrophication and ecotoxicity are more aptly assessed by LCA.
3. **Nutrient leaching from fields** – measurement of the leaching of nutrients such as nitrogen and phosphorus is difficult, and when conducted offer a range of values. In order to make the grey water footprint more specific to the actual mills' situation, it would be desirable to conduct measurements in the mills' plantations, and to assess related data that may become available from external studies (e.g. scientific publications and reports).
4. **Pesticides and herbicides leaching and impacts on water** – similar to nutrient leaching, the behaviour of pesticides and herbicides has to be investigated, and their impact on water established. It is important to keep in mind that the grey WFP of Braskem's biobased PE does currently not take any impacts from pesticides/herbicides into account because of a lack of available data.
5. **Precipitation monitoring** – even though blue water in the Paraná Basin currently is not scarce, and all sugar cane grows in completely rain-fed plantations, much of the future sustainability does depend on precipitation in the region. It is important to understand potential future changes to precipitation in order to assess the suitability of current plantations for future use, as well as to identify future expansion areas from a green water availability perspective.
6. **Water scarcity and quality in the South Atlantic Basin** – as soon as more detailed data describing the situation of water in the South Atlantic (and the Paraná River) Basin become available, a renewed assessment of the sustainability of the biobased PE water footprint should be made in light of the new data.
7. **Irrigation of sugar cane in Brazil** – most of the sugarcane plantations in Brazil are currently not irrigated. However, it is possible that irrigation may become necessary if sugar cane plantations expand onto drier soils, and it is recommended to further study both likelihood and timeline of this possibility.

Conclusion

Through these studies, Braskem taken important steps in understanding of the main potential environmental impacts of its biobased PE and has identified a number of points that will benefit from further work, continuous monitoring, and the prioritisation of future improvements.

In terms of the main results, biobased PE was identified as having a good performance in the GWP_{100} and Abiotic Depletion Potential impact categories. Comparative whole life cycle assessments on PE products will be a next step to indicate how these cradle-to-gate benefits contribute when appropriate use and end of life phases are brought into the assessment. Other impact categories show more heterogeneous results with petrochemical PE showing advantage over biobased PEs in some impact categories. To come to a conclusion on the relative importance of individual impact categories, it is necessary to understand their significance or weighting (essentially a value judgement) in any integration process to generate an overall indicator of absolute impact on the environment. Such 'integrated assessment' models are the subject of ongoing debate and discussion and, for the present time, we believe that the greatest clarity and understanding is obtained from evaluating the impacts of biobased PE on a category-by-category and individual issue basis.

The improvement analysis in the LCA has provided an understanding of areas for continuing improvement that can be integrated in Braskem’s environmental management systems, and be further monitored.

It is also clear that the absolute values of the results vary depending on the choice of LCA methodology. We consider, however, that the substitution-based approach used is appropriate in relation to the study's goals, is transparent and qualified, and is a reasonable representation of the system impacts of Braskem's biobased PE production.

In terms of land use change, the impacts are relatively low, with possibly positive direct LUC and negative indirect LUC. Actively supporting national land use planning and identification of suppliers expanding onto degraded land will be important going forward in order to minimise indirect LUC impacts.

The water footprint study showed that there are no immediate significant water impacts, but that the local water situation requires continued monitoring to identify and prevent the development of new hotspots.

The results of these studies will now form the basis of further technical developments within Braskem and will inform discussions and collaboration with stakeholders.